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Electrified Transportation System Performance: Conventional vs. Online Electric Vehicles

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***Abstract*—In recent years, the electrification of ground transportation has emerged as a trend to support energy efficiency and CO_2 emissions reduction targets. The true success, however, of this trend depends on the successful integration of electric vehicles into the infrastructure systems that support them. Left unmanaged, conventional electric vehicles may suffer from delays due to charging or cause destabilizing charging loads on the electrical grid. Online electric vehicles have emerged to remediate the need for stationary charging and its effects. This chapter seeks to objectively compare the systemic impacts of these two electric vehicle concepts on the combined electrical power grid and road transportation system. It applies a recently developed hybrid dynamic system model of the transportation-electricity nexus that holistically incorporates vehicle dispatch, route choice, charging station queues, coordinated charging, and vehicle-to-grid stabilization. It draws upon Axiomatic Design for Large Flexible Engineering System Theory to superimpose a marked petri-net model layer on a continuous-time kinematic and electrical state evolution. The results show that online electric vehicles, unlike their conventional vehicle counterparts, are able to avoid charging station queues and thus are able to meet the needs of a greater variety of transportation uses cases including commercial and public fleets. Their impacts on the power system also differ. While conventional electric vehicles are likely to require greater investment to expand power system generation capacity, online electric vehicles are likely to incur greater operating costs to manage their charging loads. The chapter concludes with several directions for future work in the development of intelligent-transportation-energy systems which can serve to reduce both costs for both vehicle concepts.**

I. Introduction

In recent years, electrified transportation has emerged as a trend to support energy efficiency and CO_2 emissions reduction targets [1]–[5]. Relative to their internal combustion vehicle (ICV) counterparts, electric vehicles (EV), be they trains, buses, or cars, have a greater "well-to-wheel" energy efficiency [5], [6]. They also have the added benefit of not emitting any carbon dioxide in operation and rather shift their emissions to the existing local fleet of power generation technology [7].

The success of electric vehicles depends on their successful integration with the infrastructure systems that support them. From a transportation perspective, conventional electric cars typically only have a short-range of 150km [8] but may still require several hours to charge [9]. This affects when a vehicle can begin its journey and the route it intends to take. From an electricity perspective, the charging loads can draw large power demands which may exceed transformer ratings, cause undesirable line congestion, or voltage deviations [10]–[13]. These loads may be further exacerbated temporally by similar charging patterns driven by similar work and travel lifestyles or geographically by the relative sparsity of charging infrastructure in high demand areas [11]. In effect, the electric vehicles and their supporting charging infrastructure couples the transportation and electrical systems into a nexus.

Definition 1. Transportation-Electricity Nexus (TEN) [14]: A system-of-systems composed of a system with the artifacts necessary to describe at least one mode of transport united with an interdependent system composed of the artifacts necessary to generate, transmit, distribute and consume electricity.

As a result, the performance in the transportation domain cannot be studied independently of the performance in the electrical domain. Furthermore, efforts to operate and control the performance in either domain require an assessment model whose scope includes the functionality of both systems. Consider an EV taxi fleet operator [11]–[13]. They must dispatch their vehicles like any other conventional fleet operator, but with the added constraint that the vehicles are available after the required charging time. Once en route, these vehicles must choose a route subject to the nearby online (wireless) and conventional (plug-in) charging facilities. In real-time, however, much like gas stations, these charging facilities may not be available due to the development of queues. Instead, the EV taxi driver may opt to charge elsewhere. Once a set of EV taxis arrive at a conventional charging station, the EV taxi fleet operator may wish to implement a coordinated charging scheme [15]–[26] so as to limit the charging loads on the electrical grid. The local electric utility may even incentivize this EV taxi operator to implement a "vehicle-to-grid" scheme [27]–[29]to stabilize variability in grid conditions. The aforementioned five transportation-electric nexus operations management decisions are summarized in I. While these decisions are coupled, the degree to which they can be coordinated ultimately depends on the presence of a well-designed Intelligent Transportation-Energy

System (ITES) [12].

Table I: Intelligent Transportation-Energy System Operations Decisions in the Transportation Electricity Nexus

- **Vehicle Dispatch**: When a given EV should undertake a trip (from origin to destination)
- **Route Choice**: Which set of roads and intersections it should take along the way
- **Charging Station Queue Management**: When & where it should charge in light of real-time development of queues
- **Coordinated Charging**: At a given charging station, when the EVs should charge to meet customer departure times and power grid constraints
- **Vehicle-2-Grid Stabilization**: Given the dynamics of the power grid, how can the EVs be used as energy storage for stabilization

Designing such an intelligent transportation-energy system requires a careful assessment of the couplings between the kinematic and electrical states in a TEN. Thus far, to our knowledge, only two works have been able to assess this coupling. A simplified study based on the city of Berlin was implemented on MATSIM [30]. Meanwhile, the first full scale study was completed in the city of Abu Dhabi [11]–[13] using the Clean Mobility Simulator [31]. The former assumed a home-charging (i.e. always available) use case and thus neglected the impacts of charging station capacity on the transportation system as well as on the power system. The latter study sought a more holistic approach to system performance measurement. "Quality of Service" (QOS) [11], [13] was introduced as a transportation performance measure to address the availability concerns expressed in EV adoption public attitude surveys. Meanwhile, power system line and bus safety criteria were introduced on the basis of IEEE reliability standards [11]–[13]. The methodologies for the performance assessment of a TEN are still very much in the course of development. As part of its methodological contribution, this book chapter also quantifies the required additional power system operating reserves and generation capacity.

This chapter's primary contribution is to objectively compare the systemic impacts of both electric vehicle concepts on the transportation-electricity nexus. This require several notable contributions to the existing literature. Of the two previously mentioned studies, neither considered online electric vehicles; either on their own or relative to their conventional electric vehicle counterparts. Thus, this chapter makes a methodological contribution in how to conduct such an assessment. To that end, it uses the recently developed hybrid dynamic model (HDM) for a transportation-electricity nexus [14]. It draws upon Axiomatic Design for Large Flexible Engineering System Theory [14], [32]–[41] to superimpose a marked petri-net model layer on a continuous-time kinematic and electrical state evolution. This work, therefore, also represents the first application of the model to a moderately sized system. This system is a newly developed transportation-electrification test case which objectively draws out the differences between online and conventional electric vehicles. The model also serves as the basis for a newly developed transportation-electricity nexus simulations. Together, these contributions enable an objective comparison of the two transportation electrification concepts. The results show that online electric vehicles, unlike their conventional vehicle counterparts, are able to avoid charging station queues and thus able to meet the needs of a greater variety of transportation use cases including commercial and public fleets. Their impacts on the power system also differ. While conventional electric vehicles are likely to require greater investment to expand power system generation capacity, online electric vehicles are likely to incur greater operating costs to manage their charging loads.

The book chapter, therefore, proceeds as follows. Section II presents the hybrid dynamic model for a transportation-electricity nexus. Section III then details the test case used to make the comparison. Section IV provides the rationalization for the new simulator. The results & discussion of the work are then presented in Section V. The work is concluded in Section VI. Finally, Section VII provides some insights for future work within the context of Intelligent Transportation-Energy Systems so as to reduce costs for both vehicle concepts.

II. Transportation Electricity Nexus Hybrid Dynamic Model

This section describes the recently developed transportation-electricity nexus hybrid dynamic model [14] in five steps. Prior to proceeding, it assumes a sufficient formal background in graph theory [42]–[44] and petri nets [45]–[47] which is otherwise obtained in the Appendix. The section begins with a rationale for such a model and then describes its development. Next, it applies Axiomatic Design for Large Flexible Engineering SystemsTheory. [14], [32]–[41]. The resulting system knowledge base is then used to construct a timed petri-net model [14]. This gives the added advantage of describing the system state in a distributed fashion that more intuitively represents the microscopic flow of vehicles within a transportation system. The events of fixed duration are then replaced with continuous-time differential equations that describe the kinematic and electrical state evolution of each vehicle. The section concludes with a description of model outputs of greatest interest.

A. The Need for a Hybrid Dynamic Model

The assessment of holistic system performance for a transportation-electricity nexus requires an equally holistic system model. As has been previously argued in the case of the energy-water nexus [48], [49], the main challenge in transportation electrification is that engineers are typically trained within disciplines (e.g. mechanical, electrical, chemical, civl) rather than broad-scoped problem areas such as transportation-electrification. This often leads to *silo* thinking that generates piece-meal technical solutions that are restricted by the boundaries, competences, and methods of the respective engineering field. Nevertheless, if many of the traditional methods from multiple disciplines are combined into a single analytical model then new effective solutions can be developed that target the main technical barriers at the heart of problem.

That said, a transportation-electricity nexus model is not simply a traffic-simulation model stitched to a power system model. The whole, in form and function, is very much likely to be greater than the sum of the parts. Instead, integrated technical modeling frameworks that transcend the traditional boundaries of the various engineering disciplines are required.

Graph theory is often proposed as such a modeling framework in many application domains [42]–[44]. Indeed, many models of transportation [50]–[54]and power systems [55], [56] rely upon the graph theoretic definitions provided in the Appendix. In transportation systems, the nodes often physically represent intersections and stations while edges/arcs represent roads, rails or transportation routes. In power systems, the nodes often physically represent generators, substations, and loads while the edges represent the road embedded power cable modules. This is an abstracted model of a system's form; neglecting an *explicit* description of the system's function [57]. Thus, in detailed engineering, it becomes difficult to link nodes and edges to physical variables of engineering physics. Furthermore, graph theoretic application domains are restricted to large flexible *homo-functional* engineering systems where artifacts (of some kind) are transported between physical locations. While transportation functions from one location to another are fundamentally different, ultimately they are of the same type. Thus, it is less than clear how graph theory may be applied to systems like the transportation-electricity nexus that span multiple energy domains and are thus fundamentally *hetero-functional*. In summary, graph theory does not do the following [14], [38]–[40]

1) Explicitly differentiate between heterogeneous modes of transport with fundamentally different graphs for each
2) Explicitly describe the system function, especially functions that do not involve a type of transportation.
3) Explicitly describe "null-processes" (i.e. the process of staying in the same location).
4) Facilitate further detailed engineering design in terms of system function and form.
5) Facilitate the description of faulted, or intentionally offline functionality to support reconfigurable operation.

B. Axiomatic Design for Large Flexible Engineering Systems

To overcome the limitations described above, the hybrid dynamic model builds upon Axiomatic Design for Large Flexible Systems Theory where the allocation of system function to system to system form is explicitly described.

Definition 2. Large Flexible Engineering System (LFES) [39]–[41]: an engineering system with many functional requirements that not only evolve over time, but also can be fulfilled by one or more design parameters.

In the context of this work, the *functional requirements* and *design parameters* mentioned in Definition 2 are understood to be *mutually exclusive and collectively exhaustive* sets of the system's processes (P) and resources (R) respectively. This change of terminology is applied consistently for the rest of the chapter.

The system resources $R = B \cup H$ may be classified into a set of stations $B = \{b_1 \dots b_{\sigma(B)}\}$, and transporting resources $H = \{h_1 \dots h_{\sigma(H)}\}$ [14], [32]–[40]. Depending on the nature of the design problem, previous work has interpreted these resources as vehicles [34]–[36], stations, or even whole modes of transport [37], [38]. In (traditional) transportation systems, the system processes are taken as the set of transportation processes.

Definition 3. Transportation Process [34]: Given an arbitrary origin station b_{y_1} and an arbitrary destination b_{y_2} within a set of stations B, a transportation-resource-independent process $p_\tau \in P_T$ transports individuals between b_{y_1} and b_{y_2}. A convention is adopted between the indices of stations and transportation processes such that:

$$\tau = \sigma(B)(y_1 - 1) + y_2 \tag{1}$$

where the $\sigma()$ gives the size of a set.

There are $\sigma^2(B)$ such transportation processes of which $\sigma(B)$ are "null processes" where no motion (i.e. the parking process) occurs. Note that these transportation processes are analogous to the *potential* edges between nodes and the self-loops in a traditional graph. Nevertheless, they are *formally* different because the analog of an edge in Axiomatic Design requires that an edge represent a feasible combination of process *and* resource.

It is also important to note that the inclusion of the $\sigma(B)$ parking processes is essential to the TEN model. Many traffic simulation packages, perhaps due to their historical focus on road congestion management, define vehicle trips between *distinct* origins and destinations [58], [59]. The parking processes, at best, have little to add in that regard and can be left out of the scope of simulation. At worst, they dramatically expand the number of vehicles participating in the evolution of the traffic system's state. In a transportation electricity nexus, however, many of these parking functions are also associated with charging, and thus can not be neglected. Thus, transportation-electricity nexus modeling must be done from the perspective of the traveler and thus is consonant with ongoing multi-agent system trends in future urban transportation systems [60], [61].

The essential axiomatic design activity of mapping function to form is then completed via a LFES knowledge base.

Definition 4. LFES Knowledge Base [14], [32]–[40]: A binary matrix J_S of size $\sigma(P) \times \sigma(R)$ whose element $J_S(w,v) \in \{0,1\}$ is equal to one when action (in the SysML sense) e_{wv} exists as a system process $p_w \in P$ being executed by a resource r_v in R.

The axiomatic design equation for large flexible engineering systems then mutually relates the system processes and resources [14], [32]–[40]

$$P = J_S \odot R \tag{2}$$

where $\odot$ is the boolean equivalent of matrix multiplication [14], [32]–[40]. It intuitively means that a given system process p_w can be fulfilled by a system resource r_v ***or*** any other resource as long as $J_S(w,v)=1$. This a fundamentally different design equation than the one used in axiomatic design for large fixed systems described extensively in the previous chapters of this book because the mapping between function and form is based upon an ***OR*** relationship rather than an ***AND*** relationship. Consequently, the independence axiom remains fulfilled between process p_w and resource r_v even if additional processes and resources are added. As a result, there is no requirement that $\sigma(P)=\sigma(R)$ in LFESs.

From a graph theory perspective, the system knowledge base itself forms a bipartite graph which maps the set of system processes to their resources. Unlike traditional graph theory, however, the explicit treatment of system processes in Axiomatic Design allows the study of hetero-functional large flexible engineering systems such as production systems [32]–[36], [39], [40], [62]–[64], power systems [65], water distribution systems [40], [62], their nexus [66], transportation systems [14], [37], [38] and transportation electrification [14]. Furthermore, since there are no conditions placed on the heterogeneity of the system resources, the system knowledge base also succinctly suffices to describe multi-modal transportation systems with fundamentally different graphs (e.g. rail and road networks).

The LFES Knowledge Base in Definition 4 is then sufficient to define a knowledge base for (traditional) transportation systems.

Definition 5. Transportation System Knowledge Base [14], [37], [38]: Given a set of transportation processes P_T and a set of transportation resources R, an action $\epsilon_{\tau v}\in\mathcal{E}_T$ can be defined for each feasible combination of transportation process $p_{t\tau}$ being realized by resource r_v. The Transportation System Knowledge Base J_T is a binary matrix of size $\sigma(P_T)\times\sigma(R)$ where element $J_T(\tau,v)\in\{0,1\}$ is equal to one when action $\epsilon_{\tau v}$ exists.

A careful inspection of Definitions 4 and 5 shows that traditional transportation systems assume that $P=P_T$. In the transportation electricity nexus, however, this assumption is not true because charging functionality is not considered. The transportation processes alone do not form a *collectively exhaustive* set of the system processes.

The derivation of the TEN knowledge base, therefore, requires the introduction of a set of charging processes.

Definition 6. Charging Process: A resource-independent process $p_c\in P_c$ that positively or negatively affects an electric vehicle's state of charge (SOC). These processes may draw or inject the required energy into the interdependent electricity grid.

In the context of this work, $P_C=\{p_{c1},\ldots,p_{c4}\}$ where

- p_{c1} – null charging does not change the electric vehicles state of charge
- p_{c2} – discharge the EV SOC to the electric vehicle's propulsion system
- p_{c3} – charge the EV SOC by wire
- p_{c4} – charge the EV SOC wirelessly

At this high level of design, no assumption is made on sign (or directionality) of the power transfer. These processes may be further differentiated depending on the need for different rates of SOC change. These processes may be realized by the set of transportation resources R. Conventional (non-electrified) stations effectively implement p_{c1} while conventional roads implement p_{c2}. Charging stations and electrified rails are capable of p_{c3} regardless of whether they are simply charging or implementing more advanced "vehicle to grid" technology [27]–[29]. Finally, the electrified roads associated with OLEVs [67]–[70] described throughout much of this book are capable of p_{c4}.

From the set of charging processes, the associated charging system knowledge base is defined.

Definition 7. Charging System Knowledge Base: Given a set of charging processes P_c and a set of transportation resources R, an action $\epsilon_{\kappa v}\in\mathcal{E}_C$ can be defined for each feasible combination of charging process $p_{c\kappa}$ being realized by resource r_v. The Charging System Knowledge Base J_C is a binary matrix of size $\sigma(P_C)\times\sigma(R)$ where element $J_C(\kappa,v)\in\{0,1\}$ is equal to one when action $\epsilon_{\kappa v}$ exists.

The derivation of the TEN knowledge base then requires that the *collectively exhaustive and mutually exclusive* system processes be defined from among the feasible combinations of transportation and charging processes. For example, these can include "staying in place at b_{y1} while charging by wire" or "moving from b_{y1} to b_{y2} while charging wirelessly". While the system knowledge base can be constructed manually by inspection such an approach is ultimately tedious given its size. Instead, it is more readily obtained from the much smaller transportation and charging knowledge bases.

$$J_S=\left[J_C\otimes\mathbf{1}^{\sigma(P_T)}\right]\cdot\left[\mathbf{1}^{\sigma(P_C)}\otimes J_H\right] \tag{3}$$

where $\otimes$ is the Kronecker tensor product and $\mathbf{1}^n$ is a ones vector of length n.

Interestingly, the LFES knowledge base has an additional property in that it defines the system's scleronomic (i.e. sequence-independent) degrees of freedom [34].

Definition 8. Scleronomic Transportation Degrees of Freedom [14], [37], [38]: The set of independent transportation actions $\mathcal{E}_S$ that completely defines the available transportation processes in a transportation system. Their number is given by:

$$DOF_S=\sigma(\mathcal{E}_S)=\sum_{w}^{\sigma(P)}\sum_{v}^{\sigma(R)}J_S(w,v) \tag{4}$$

Ultimately, the Axiomatic Design for Large Flexible Engineering Systems theory is a sufficiently rich foundation to describe the structure of a transportation-electricity nexus. The next subsection turns to defining its discrete-event system dynamics.

C. A Timed Petri-Net Model

In this subsection, the TEN's scleronomic degrees of freedom are used to establish a timed petri-net model. As with the previous discussion on graph theory, a formal background in petri-nets is assumed and is otherwise obtained in the Appendix. In developing the timed petri-net model, the emphasis was placed on maintaining its *intuitive* link to the physical reality. Therefore, Definition 24 of a timed petri-net is given the following physical meaning:

Definition 9. Transportation Electricity Nexus Timed Petri Net: A timed petri net where

- B, as the set of places, represents transportation stations.
- $\mathcal{E}$, as the set of discrete events, represent the scleronomic degrees of freedom (as defined in the previous section).
- M, as the set of arcs, represent the logical relationship from the events to the places and from the places to the events.
- $W : M \to \{0, 1\}$ is the weighting function on the arcs.
- Q_B , as the place marking (or discrete state) vector, represents the the queue of vehicles at a given transportation station awaiting an event.
- $Q_{\mathcal{E}}$, as the event marking vector, represents the number of vehicles undergoing the events (e.g. parking, charging, moving from one place to another).
- D, as the event durations, represent the duration of time that each event requires for completion.

The physical meanings of Q_B and $Q_{\mathcal{E}}$ are particularly important and are subtly different from many other petri-net models. In this model, parking is explicitly modeled as a transition with its associated timing, duration, & required capacity. In the case of conventional parking, this is assumed to occur immediately upon arrival. The leftover tokens in Q_B represent the electric vehicles that have arrived at a charging station and are awaiting their place in a queue for the associated charging event. It has a direct impact on an electric vehicle's utilization. The tokens in $Q_{\mathcal{E}}$ directly affect the utilization of parking lots and charging stations and the congestion in conventional and electrified roads.

The discrete-event dynamic evolution of the timed petri-net is then given by Definition 25:

$$Q_B[k+1] = Q_B[k] \quad + \quad M_{\mathcal{N}}^{+}U_k^{+} \quad - \quad M_{\mathcal{N}}^{-}U_k^{-} \qquad (5)$$

$$Q_{\mathcal{E}}[k+1] = Q_{\mathcal{E}}[k] \quad - \quad U_k^{+} \quad + \quad U_k^{-} \qquad (6)$$

where the input firing vectors U_k^- are derived from the traffic demand data, which provide the following information:

- when a given vehicle will begin a trip from origin to destination
- which route (i.e. sequence of roads) it will take.
- how long it will remain at its destination
- when it will charge along the way (while moving or parked)

Naturally, a given vehicle $l \in L$ will take several trips over the course of the day and a transportation-electricity nexus model must equally consider when the vehicle is parked as when it is moving.

This traffic demand data is most easily captured in a vehicle firing matrix $\mathcal{U}_k$.

Definition 10. Vehicle Firing Matrix: a binary vehicle firing matrix $\mathcal{U}_k$ of size $\sigma(\mathcal{E}_S) \times \sigma(L)$ whose element $\mathcal{U}_k(\psi, l) = 1$ when the k^{th} firing timing triggers a vehicle l to take scleronomic degree of freedom ψ for action.

Consequently, the input firing vector for the timed petri net U_k^- is easily calculated.

$$U_k^- = \mathcal{U}_k \mathbf{1}^{\sigma(H)T} \qquad (7)$$

The calculation of the output firing vectors is explained in the Appendix.

D. Refinement to a Hybrid Dynamic Model

In this subsection, the timed petri net model is replaced with a hybrid dynamic model. While the timed petri-net model has significant advantages in terms of its simplicity, it assumes fixed duration events which are better replaced by variable durations determined by a set of continuous-time differential equations that describe the evolution of each vehicle. The development of the hybrid dynamic model gains its inspiration from hybrid automata [45]. To that effect, it is defined as follows:

Definition 11. Transportation Electricity Nexus Hybrid Dynamic Model: A 10-tuple $\mathcal{H} = (B, \mathcal{E}, M, W, Q, \Phi, U, X, F, domain)$ where

- $(B, \mathcal{E}, A, W, Q)$ is the underlying marked petri net (Definiton 9).
- Φ is the discrete state petri-net transition function (Definition 23),
- $\mathcal{U}$ is a binary vehicle firing matrix (Definition 10).
- $X = [x_1, \ldots, x_{\sigma(L)}]$ is a continuous-time vector representing the kinematic and electric state of each vehicle in a fleet of size $\sigma(L)$.
- f is a vector field. $f : Q \times X \times U \to X$. It describes the continuous-time evolution of these vehicles.
- $domain$ is a set of invariant conditions [45] which associates a discrete state Q to an interval of X and U within which X and U must remain in order to also remain in the discrete state Q.

The state x_l must represent the kinematic and electrical state of a given vehicle $l \in L$. While the model can easily accommodate an elaborate description of the vehicle's internal dynamics, it is important to recall that doing so might be practically infeasible given the shear number of vehicles being simulation within the TEN. To that effect, a minimalistic model is chosen. $x_l = [z_l, \dot{z}_l, s_l]^T$ where

- z_l – is the distance of the vehicle along a road segment in relative coordinates
- $\dot{z}_l$ – is the speed of the vehicle along the road segment
- s_l – is the vehicle's state of charge.

The vector field f is implemented as a state space differential equation of the form:

$$\dot{X} = f(Q, X, U_k) \qquad (8)$$

In free driving conditions, the dynamics of each vehicle become entirely uncoupled and the state of the vehicle becomes purely a function of the vehicle firing matrix.

$$\begin{bmatrix} \dot{z}_l \\ \ddot{z}_l \\ \dot{s}_l \end{bmatrix} = \begin{bmatrix} \beta_v \\ 0 \\ \alpha_v \end{bmatrix} U_{kl} \tag{9}$$

The vehicle speed is set to a constant speed β_1 whether it is moving along a road or parked at a station. Additionally, the charging rate α_1 is sufficient to describe all four types of charging processes. One advantage of the free-driving model is that it retains the timings of the underlying timed petri-net model. In contrast, under more normal driving conditions with some congestion a car following model is typically used [59], [71], [72]. Consequently, the state of charge is often modeled to change with the vehicle speed and vehicle firing matrix.

$$\begin{aligned} \dot{z}_l &= \dot{z}_l \\ \ddot{z}_l &= \alpha \dot{z}_l^{\beta}(t) \tfrac{(\dot{z}_{l-1}(t-T) - \dot{z}_l(t-T))}{(z_{l-1}(t-T) - z_l(t-T))^{\gamma}} \\ \dot{s}_l &= f(\dot{z}_l) + \alpha_v U_{kl} \end{aligned} \tag{10}$$

where $\ddot{z}_l$,$\dot{z}_l$,z_l are the acceleration,speed and position of the l^{th} vehicle which follows the $l-1$ vehicle. $\alpha > 0$, β and γ are model parameters that control the proportionalities and T is reaction time [71], [72].

Finally, the *domain* describes a set of invariant conditions upon which a given discrete state remains valid. In the context of the HDM, these conditions are useful for constraining the vehicles distance along the road segment and its state of charge within limits. For example,

$$\begin{aligned} 0 &\le z_h \le & z_{vmax} \\ 0 &\le s_h \le & S_{hmax} \end{aligned} \tag{11}$$

where D_v may be the road length and S_{hmax} may be the vehicle's battery capacity.

E. Hybrid Dynamic Model Outputs

To conclude the definition of the hybrid dynamic model, it is important to identify relevant model outputs for subsequent discussion. As previously mentioned, the model was developed to maintain a highly intuitive nature. The place marking vector Q_B represents the queue of vehicles at a given station. It is important as a model output to measure the number of electric vehicles waiting to be charged. The event marking vector itself $Q_{\mathcal{E}}$ represents the number of vehicles undergoing the events. It can be divided into the number of vehicles flowing in roads, and the number of parked vehicles. Finally, the total charging load f_c – the net load required by the TEN from the power system – is easily found as a linear combination of the elements in the event marking vector.

$$f_c = C_{\alpha}^T Q_{\mathcal{E}} \tag{12}$$

where C_α is a vector of size $\sigma(\mathcal{E})\times 1$ whose elements $C_\alpha(v) = \alpha_v$, the charging rate in kilowatts for the given event.

III. Transportation-Electrification Test Case

With a hybrid dynamic model for the transportation electricity nexus in place, the chapter shifts focus to the comparison of electrified transportation system performance in the cases of conventional and online electric vehicles. To that end, it is necessary to use a transportation-electrification test case that does not create undue bias between the scenarios. Indeed, one critique of the traffic simulation literature is that it focuses on specific traffic topologies rather than investigating the fundamental dynamics of traffic behavior [73]. Furthermore, a test case must be of a sufficiently moderate size to predict how the scenarios may scale up to a full deployment. Finally, the electrification topology should be regular enough to facilitate the interpretation of how the system performance emerges from the system behavior in the respective scenarios. Furthermore, it must be of a sufficiently moderate size to predict how the scenarios may scale up to a full deployment. Finally, the electrification topology should be regular enough to facilitate the interpretation of how the system performance emerges from the system behavior in the respective scenarios. With these considerations in mind, and in the absence of a real-life test case with the same attributes, a hypothetical test case aptly named "Symmetrica" was developed. While its specific characteristics may differ from the reality of specific regions, its characteristics do offer much in developing insight and intuition into the dynamics of transportation-electricity nexus. For the sake of simplicity, and without loss of generality, the roads are assumed to be free of congestion and the free-driving model will then be applied.

A. Road Topology

The Symmetrica road topology is shown in Figure 1. It is a suburban 12x12km grid with intersections at every kilometer. Each road segment has a free speed of 60km/hr.

B. Electrification Toplogies

Two electrification topologies were designed for Symmetrica. Both were designed to be able to deliver a maximum of 46.8MW of charging load – the size of a medium capacity generator. The equivalence in the peak charging rate between the two scenarios was introduced to avoid biasing effects on vehicle travel patterns, and power system balance. For simplicity, the charging infrastructure was also assumed to come with the necessary upgrades in line, transformer and substation capacities to support the charging. Electric vehicle charging in private residences do pose such a challenge, but it is specifically neglected in this work. Consequently, this work does not address the local line and voltage safety criterions found in recent work [10]–[13]. Furthermore, this work assumes that the two electrification scenarios have equivalent investment cost and instead addresses the additional costs required to mitigate the effects of charging on the power system. The details of each scenario are as follows.

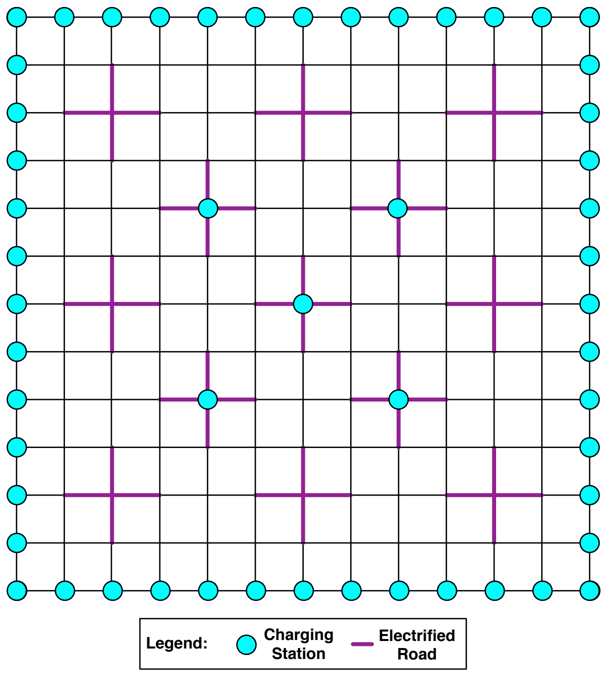

Fig. 1: Topology of the Symmetrica Transportation Electrification Nexus

1) Conventional Electrification Topology: The conventional electrification topology consists of two groups of charging stations. There are 5 charging station in the city center at coordinates (4,4), (4,8), (8,4), (8,8) and (6,6). These are marked as cyan circles in Figure 1. Each of these can deliver 30kW to each of 25 vehicles at a time. In order to include the potential for home charging, a charging station was placed at every intersection along the periphery, each delivering 18kW to each of 50 vehicles at a time. It is important to note that a given intersection here does not represent an individual home where there may only be 1 or 2 spaces to charge in a garage. Instead, the intersections along the periphery represent all of the homes associated with the vehicles that exited Symmetrica through that intersection. Thus, it is a centralized representation of a distributed charging capacity outside of the city. In theory, full electric vehicle deployment suggests ubiquitous home charging and thus this capacity is infinite. (Every vehicle owner should be able to return home to charge). However, a fair comparison with the online electric vehicle case requires that the installed charging capacity of scenarios be equal. Here, the total installed charging capacity is (5)(0.03)(25)+(48)(0.018)(50)=46.8MW.

2) Online Electric Vehicle Topology: The online electric vehicle topology consists of 13 groups of electrified road segments which appear in Figure 1 as magenta-colored 2km x 2km road crosses. Each road segment is able to deliver 30kW to each of 28 vehicles at a time. In order to clearly distinguish the differences in system performance between the two electrification scenarios, this scenario assumes no stationary charging. This electrification scenario is also capable of delivering up to (4)(13)(0.03)(30)=46.8MW of power.

C. Traffic Demand

The traffic demand represents a simplification of an average work day. Symmetrica starts the day empty of any vehicles. Vehicles enter from any of the intersections along the symmetric periphery and go to five work locations which coincide with the five conventional charging stations depicted as cyan circles. In such a regular topology, there are many "shortest route" choices between a given origin and destination. For example, there are 6 such routes just from (0,0) to (2,2). The traffic demand consists of all of these shortest routes with the added constraint that such routes must pass through the centers of the electrified road segment crosses depicted in magenta. This ensures that the same traffic demand can be applied in both electrification scenarios without bias. It also serves to more evenly distribute the traffic and not place undue congestion on the electrified roads. Note that the number of routes thus follows an exponential distribution with the required distance.

The traffic demand makes use of this exponential distribution to generate the timing and congestion in the morning and evening rush hour commutes. For a given origin-destination pair, there are many possible routes. Each of these is initiated every minute, one vehicle at a time, in such a way that they are centered around 7:30am. A total of 8252 vehicles are simulated. In all, the first vehicles enter Symmetrica at 5:00am and the end of the morning commute is marked with the last vehicle at 10am. Upon arriving to the five work locations, the vehicles remain there for 8 hours and then return "home" to the Symmetrica periphery intersection from which they entered along the route that they took in the morning. No further assumption is made on the transportation use case (e.g. private usage, taxi, car sharing etc). Instead, the potential implications on use cases are discussed in connection with the results described in Section V.

D. Charging Demand

All of the electric vehicles begin the day at a full charge. The online electric vehicles are assumed to discharge power at a rate of 30kW when moving at the road free speed of 60km/hr. The conventional electric vehicles have larger batteries and thus weigh more. They are assumed to consume 20% or 36kW. The online electric vehicle battery size is a modest 2.5kWhr which is sufficient in this case to not require any conventional charging. The conventional electric vehicle battery size is a manageable size of 12kWhr. These values are within the physical limits of current technology although the dissipation rates are exaggerated given the relatively small distances in Symmetrica.

IV. MATLAB Simulation for Urban Mobility Electrification

A performance comparison was conducted by simulation in Matlab. This intentional methodological departure from many available commercial as well as open-source microscopic traffic simulation software packages was deeply considered.

Several reviews contrast their respective features and performance of these packages [58], [60], [61], [74]. No commercial packages consider electrification of roads as well as parking stations and are thus deemed inadequate. The open-source packages can potentially be retrofitted with electrification functionality. This is, however, a non-trivial *post-hoc* endeavor. As mentioned in the Axiomatic Design for Large Flexible Engineering Systems discussion in Section II-B, microscopic traffic simulators were meant to simulate vehicles *in motion* between *distinct* origins and destinations. This is adequate as long as the vehicles do not change state while parked but very much inadequate otherwise, as in the case of electrified transportation. Furthermore, online electric vehicles simulation requires that a given road have the potential to provide electrified *and* non-electrified transport. Finally, microscopic traffic simulation packages only keep track of the state of *moving* vehicles. In contrast, transportation electrification requires a state for all vehicles regardless of whether they are moving. These differences represent dramatic expansions in simulation functionality – ones that are not likely to be fulfilled by incremental tweaks but rather large scale architectural changes to the software. In contrast, the simulations presented are built directly upon the Axiomatic Design model presented in Section II. All of the required functionality is considered early in the simulator design in agreement with Axiomatic Design principles. As a result, the entire simulation straightforwardly falls upon three highly intuitive matrix-based equations of motion (Equations 5, 6, and 8). That two of these are linear further facilitates the design.

In a "Big Data" application such as microscopic transportation electrification, it is also essential to consider the computational speed of the simulation. Consider the size of the vehicle firing matrix alone: it is $\sigma(\mathcal{E}) \times \sigma(L) \times \sigma(T)$. A full scale simulation, for the traditional one day, at the traditional resolution of one second, in a moderately sized city such as Abu Dhabi, would require approximately $15e3 * 1e6 * 8.64e4 = 1.2960e15$ elements. Therefore, a well-considered simulation must employ 1) matrix representations rather than scalar approaches; 2) sparse matrix techniques and advanced numerical methods; 3) parallel processing wherever possible; and 4) efficiently compiled code.

In contrast to other simulation packages implemented in JAVA and C++, MATLAB was chosen as an implementation platform. Software development in MATLAB is known to be as easy as other high level languages such as JAVA. Furthermore, it is purposefully built to handle matrix operations. It also has advanced libraries to support sparse matrices, the solution of differential equations and other advanced numerical methods. Recent versions of MATLAB also offer significant parallel processing functionality to leverage modern multi-core processors and graphical processing units. Finally, although MATLAB is an interpreted language to facilitate development, final version code can be easily compiled into C or GPU code for further performance enhancements. These features have been repeatedly tested and demonstrated across several application domains and thus represent proven technology. In contrast, simulation in JAVA and C++ would likely require custom and expert development of many of these advanced functionalities; thus expanding development time and cost.

Finally, the development of a simulations that are founded upon a rigorous dynamic model opens the door for the development of control and optimization methods as part of an intelligent transportation-energy system.

V. Results & Discussion

The results of the Symmetrica test case are now presented. The discussion addresses four areas of transportation electricity nexus performance. The first two address the transportation system: 1) the traffic behavior of moving & parked vehicles and 2) the charging behavior as a queue and electrical load. The last two address the implications on the power system assuming no corrective action was taken in the transportation system: 3) the implications on power system generation capacity and 4) the implication on the required power system operating reserves. Each of these is now addressed in turn below. Figure 2 summarizes many of the simulation results within one holistic framework.

A. Traffic Behavior: Moving & Parked Vehicles

The top two subplots of Figure 2 show the Symmetrica traffic behavior between 5am and just past 6:30pm. The number of driving vehicles on any given road segment is shown with a distinct color. In the hybrid dynamic system model, this corresponds to the rows of Q_E that are associated with events along road segments. As expected, both the online and conventional electrification scenarios reflect the traffic demand which has two exponentially distributed peaks of traffic congestion corresponding to the morning and afternoon commutes. These are qualitatively the same but numerically different. Note that the conventional electrification scenario has peaks of 37 and 34 vehicles while the online electrification scenario has peaks of 27 and 24. This difference is caused by the online electrification scenario having two events along electrified roads and not just one. As a result, the associated traffic is divided amongst them. In actuality, the physical road still carries the same number of vehicles. It is also worth noting that the two scenarios demonstrate the same timing for the afternoon commute. This suggests that the 8 hours devoted to work were sufficient to allow all electric vehicles to depart without delay. Therefore, both electrification scenarios demonstrate a 100% quality of service [11]–[13] for this specific use case.

The next two subplots in Figure 2 show the quantity of parked vehicles in Symmetrica's parking lots. In the hybrid dynamic system model, this corresponds to the rows of Q_E that are associated with parking events at the five work locations. As expected, the number of parked vehicles rises sharply shortly after the peak congestion times and eventually stabilizes as moving vehicles reach their workplace. Note that the number of parked vehicles in the conventional electrification scenario appear delayed despite the equivalent traffic behavior timing in the previous two plots. This is because the

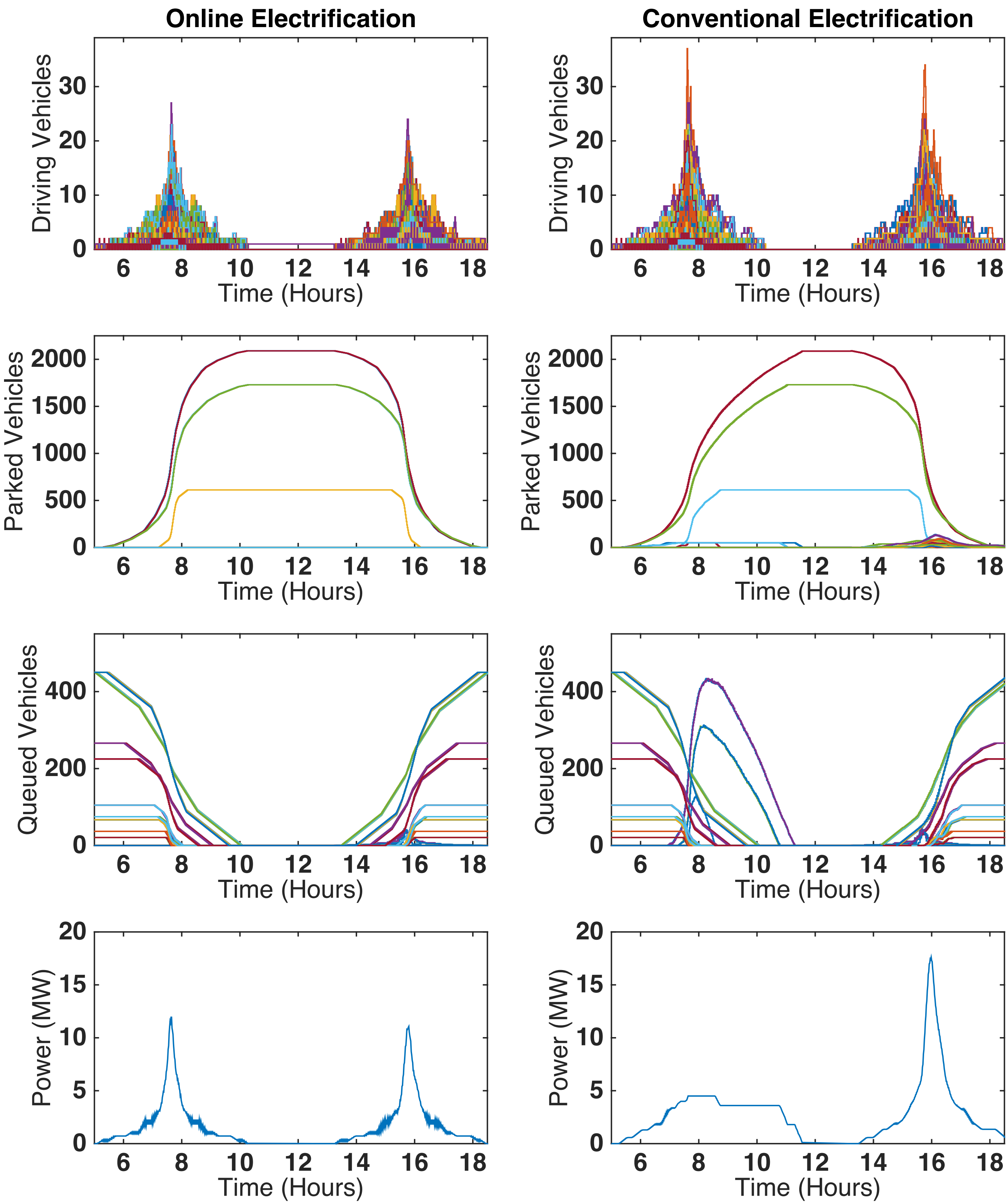

Fig. 2: Simulation Results of the Symmetrica Test Case for Online & Conventional Transportation Electrification

electric vehicles either begin or await charging upon arrival to the workplace and therefore are not counted as "non-electrifed" parking. Thus, these parked vehicles come to mean "vehicles-ready-for-usage". The equivalence of the peaks of the two plots confirms that, in this use case, the same quality of service of 100% is achieved. Also note that the numerical scale of parked vehicles is much greater than those in motion. Here, the peak is just over 2000 vehicles – two orders of magnitude greater. From a systems perspective, roads are associated with distributed quantities while parking lots are associated with centralized quantities. While this is perhaps a straightforward insight in transportation behavior, the implications on electrification infrastructure appear profoundly and are dramatic in the subsequent plots.

The next two subplots in Figure 2 show the quantity of queued vehicles in Symmetrica. In the hybrid dynamic model, this corresponds to Q_B. In the morning, vehicles in both electrification scenarios are queued at the periphery (as a representation of homes). These queues dramatically shorten over the course of the morning commute hours until they disappear. They only begin to form again in the late afternoon hours as vehicles return home. This is another way of viewing the "distributed-to-centralized-to-distributed" state evolution of the vehicle fleet over the course of the day. The obvious difference between the two electrification scenarios is the presence of queues with conventional charging stations. Online electric vehicles charge as they move. They do not form queues in the stationary sense. If the electrified road does not have sufficient capacity, then some vehicles do not receive the full amount of charge that they require. In contrast, conventional charging only completes charging once a full state of charge has been achieved. Consequently, charging queues inevitably form. It is here that the centralized state of the vehicle fleet means that more than 400 vehicles can be waiting to charge at a time. Furthermore, this queue does not clear until nearly the afternoon hours. Had this queue been longer, with perhaps an increase in the traffic demand or electric vehicle penetration rate, it could have meant that some vehicles would not be available on time for the afternoon commute home. This would represent a reduced quality of service. Alternatively, had this electrification scenario been applied to a taxi use case, then many taxis would have to wait several hours after their morning customer just to take on another fare. Such a low vehicle utilization rate could prove to be a non-starter for EV taxi adoption. In contrast, the online electric vehicle taxis could continue to operate in a seemingly perpetual way.

Thus, the Intelligent Transportation-Energy System premise posed at the beginning of the chapter manifests itself. Conventional charging of electric vehicles means that electric vehicle dispatch and route choice have immediate implications on the formation of queues and the associated quality of service. A planning centric solution would be to either expand the charging rate of the conventional chargers or to increase the number of charging slots. While this requires an added investment cost, it is well-justified if it directly improves the quality of service of the desired set of electric vehicle use cases. Alternatively, an intelligent transportation-energy system can serve to dispatch vehicles at better times, choose the best routes, and potentially defer vehicles to charging stations with shorter queues. Of course, none of these solutions are required in the case of online electric vehicles.

The next two subplots in Figure 2 show the aggregate charging load of electric vehicles in Symmetrica. In the hybrid dynamic model, this corresponds to the output function Equation 12. It is here that the differences between the two electrification concepts becomes most apparent. In the online electric vehicle scenario, charging occurs literally "on-the-go", as required, in an entirely unmitigated way, as a result of road congestion. Thus, two sharp charging peaks emerge in time with the road congestion. Consequently, this traffic demand does not cause any charging load in the late morning and early afternoon hours. In contrast, the conventional charging scenario is associated with a "stock" of vehicles and not their flow. Charging is associated with two time periods: during work and at home after the commute. For charging at work, the number of charging vehicles climbs rapidly shortly after the peak congestion. Here, the centralization of electric vehicles means that charging capacity is limited, saturates and causes charging queues. The charging load eventually falls in a step-wise fashion as the queues are cleared in the late morning hours. For home charging, the vehicle fleet is very much distributed. As a result, the charging load does not saturate and more closely resembles the sharp peak of online electric vehicles. Note that the online charging scenario has a fleeting peak charging power of 12.5MW, well below the installed capacity of 46.8MW. In contrast, the conventional charging shows two very different characteristics: an enduring level near 5MW and a sharp peak near 17.5MW. As an aside, it should be noted that the area under the charging load curve represents the total energy consumed. It is numerically greater in the case of conventional electric vehicles given the assumption of larger and heavier batteries. Managing the magnitude and shape of these charging load profiles is of ultimate importance for successful integration with future electricity grids.

Again, the premise of Intelligent Transportation-Energy System posed at the beginning of the chapter manifests itself. Transportation electrification requires electric vehicles that, at worst, do not destabilize power grid operation and, at best, are active players in its stabilization. While many vehicle-2-grid stabilization schemes have thought to make use of the parked vehicles for the provision of parked vehicles, the reality is that the potential is much greater and much more dynamic. In the conventional charging scenario, for example, it is now clear that charging station selection can serve to manage queues and thus improve the performance of coordinated charging and vehicle-2-grid stabilization schemes. That said, both control decisions only serve to flatten and elongate the charging load profile. This occurs under the assumption that the transportation use case does not in actuality impose a binding time constraint on how quickly the vehicles need to be available. An immediate trade-off appears: the charging profile can be flattened for grid stabilization or sharpened for transportation system performance. For online electric vehicles, the management of the associated charging load peaks is critical to power grid operation. Furthermore, the absence of charging stations and their queues eliminates many of the control levers found in the conventional charging scenario. Instead, vehicle dispatch and route choice can be deployed as mitigation measures. Small delays of vehicle dispatch can effectively dull a sharp charging load. Equally possible, the online electric vehicle may take a different route, travel in non-electrified lanes, or simply shield itself from the wireless charging – especially in the presence of a larger backup battery. A combination of all of these options can be easily achieved with greater coordination through an Intelligent Transportation-Energy System.

B. Required Power System Generation Capacity

The last two subplots of Figure 2 showed that electrified transportation causes a non-negligible charging load on the power grid. As previously discussed, this charging load can be ameliorated with an intelligent transportation-energy system primarily in the transportation domain. Alternatively, the unaltered charging load can be passed to the power grid for mitigation in the electrical domain. There, it is necessary to assess whether the power grid requires revised planning and operations management. This subsection addresses the first in terms of the need for additional power system generation capacity.

Traditionally speaking, the first tool in power system generation capacity planning is the load duration curve. The load profile from the previous year is taken as a time series and then sorted from high to low [75]. Figure 3 shows the load duration curve for the Bonneville Power Administration in 2013 in black. Base load units are required for the entire year, followed by "shoulder" load units for most of the year, followed by peak load units for only tens of days in the year. Generally speaking, these generation units have increasing marginal costs in the order of mention to form an upward sloping power generation supply curve. Power system generation capacity planning thus asks two important questions: 1) Will the peak load increase enough to require the installation of expensive peak load generation capacity? 2) Will the peak load broaden enough to merit a replacement of peak load capacity with shoulder load capacity? These two questions are now addressed in the case of the conventional and online electrification scenarios.

To assess these impacts, the two charging load curves were zero-padded so as to form a time series for a full day. Then, as a reasonable assumption of a worst case scenario, it was assumed that all days in the year are equivalent to the work day that had been previously simulated. This yielded two full year charging load time series. The base case was then scaled so as to be 4 times larger than the magnitude of the home charging load. This 25% value was chosen as a reasonable approximation of the percentage of all energy consumed by the transportation sector in the United States [76]. The two full year charging load time series were then added to the scaled base case. The three resulting load duration curves are shown in Figure 3: 1) a base case without electrification (black) 2)

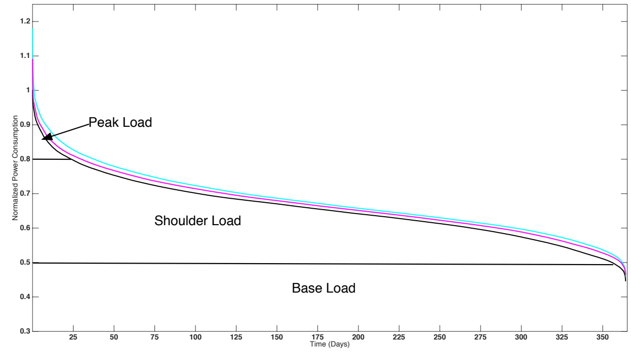

Fig. 3: Load Duration Curves: a.) base case w/o electrification (black) b.) conventional electrification (cyan) c.) online electrification (magenta)

a base case with conventional electrification (cyan) and 3) a base case with online electrification (magenta).

Simply speaking, the results show that when it comes to electric vehicle charging, timing is critical. Table II summarizes the numerical figures. Although the magnitude of the charging loads in the online electrification scenario are greater, they come during the morning and afternoon commute hours; times not traditionally associated with peak loads. Thus, the peak load expands by 8.96% (6.31 MW)– a relatively small number when compared with the maximum value of 25%. In the meantime, the midday and evening charging of the conventional electrification scenario more closely coincides with the traditional peaks of the base case load profile. Thus, the peak load expands by 17.9% (12.6 MW) even though the magnitude of the charging load was much smaller for much of the day. In 2013, the cost of a peak load advanced gas turbine was $676/kW [77]. Thus, for the provided test case, and all else held equal, the conventional charging scenario requires 4.23M$ more capital investment. It is also worth noting that in this test case neither electrification scenario was capable of flattening the the load duration curve. Therefore, there is no incentive to shift the generation portfolio from expensive peak load plants to more competitive shoulder load plants. In both cases, an intelligent transportation-energy system can serve to reduce peak loads and expand shoulder loads for even greater capital cost savings.

Table II: Effects of Transportation Electrification on Power System Peak Load Capacity & Investment Cost

	Base Case	Conventional Electrification	Online Electrification
Peak Load in MW (% Increase)	70.4 (0%)	83.0 (17.9%)	76.7 (8.96%)
Required Investment (M$)	0	8.5	4.27

C. Required Power System Operating Reserves

While it is important to assess the long term impact of charging load curves, it is equally important to recall that they present an immediate challenge to present day power grid operations. Power grid balance must be achieved at all times and at all frequencies. In the meantime, load curves arising from the electrification of transportation have frequency characteristics ranging from seconds to several hours. Therefore, the techno-economic impacts of transportation electrification on power grid operations must be assessed in a holistic manner that spans multiple timescales. Recently, the concept of power grid enterprise control has been advanced to conduct such an assessment [78], [79]. This concept was successfully used to improve the methodologies used to conduct renewable energy integration studies [80]–[83]. Such an enterprise control approach should also be applied to transportation electrification.

While a complete enterprise control methodology is outside the scope of this work, the provided data test case is sufficient to make accurate conclusions on the quantity and cost of additional power system operating reserves that are required for reliable operation. Recent research in power grid enterprise control has provided *closed-form* derivations for the required power system operating reserves given the characteristics of the net load [84]–[86].

The required quantities power system load following, ramping, and regulation reserves for the two electrification scenarios are presented in Table III. These values assume a power grid enterprise control structure similar to that of PJM-ISO with a day-ahead market time step of 1 hour, a real-time market time step of 5 minutes, and a sampling rate of 1 minute. The cost of load following reserves and regulation reserves are taken as $15.42/MW and $49.77/MW respectively [87]. For simplicity, the forecast errors on the conventional and charging loads are assumed to be zero and uncorrelated.

Table III: Effects of Transportation Electrification on Power System Operating Reserves & Costs

	Base Case	Conventional Electrification	Online Electrification
Load Following Reserves in MW (% Increase)	1.005	2.543 (153%)	1.863 (85%)
Load Following Reserve Additional Cost (k$)	0	208	116
Ramping Reserves in kW (% Increase)	103	182 (77.0%)	196 (91.4%)
Regulation Reserves in kW (% Increase)	167	247 (48.1%)	297 (78.0%)
Regulation Reserve Additional Cost (k$)	0	420	681
Total Additional Operating Cost (k$)	0	628	797

The results showed that conventional electrification required on average 0.7MW more of load following reserves leading to an difference of 92k$ of additional cost. Meanwhile, the sharp peaks associated with the online electrification scenario respectively lead to a difference of 14 and 50kW in additional ramping and regulation reserves. This accounts for 261k$ per year. In all, the online electrification scenario incurs 169k$ more in annual operating costs. In both cases, an intelligent transportation-energy system can serve to reduce the variability of charging loads at the time scale of all three types of reserves for even greater savings in operational cost.

VI. Conclusion: Conventional vs Online Electric Vehicle System Performance

In conclusion, this chapter has provided a systematic techno-economic performance assessment of conventional and online transportation electrification scenarios. It was completed with the recognition that electrified transportation effectively couples the transportation system to the electrical power grid in a "transportation-electricity nexus". To conduct the study, a hybrid dynamic model of the nexus was presented as an objective basis of comparing the two scenarios. This model was then simulated in MATLAB using a newly developed test case called Symmetria. It featured equivalent traffic demand with sufficient charging capacity in both scenarios to avoid reduced quality of service, voltage deviations or line outages. It did, however, specifically address the geographical distribution and physical capacity of the charging infrastructures. In competing the fully analysis, the chapter has also provided a methodological contribution in addition to the provided results.

The simulation results show several findings:

- The simulation of a transportation electricity nexus requires the consideration of parking and charging states in addition to the vehicle motion models found in traditional microscopic traffic simulators.
- Charging capacity limits in conventional transportation electrification causes charging queues that limit the variety of use cases to which electric vehicles are suitable. While 100% quality of service is achievable for private use cases that include charging at home and work, it is less so for commercial and public use cases.
- Online electric vehicles are well suited for all uses, particularly commercial and public uses where vehicle utilization is paramount.
- Online charging loads closely follow vehicle congestion and are likely characterized by sharp peaks.
- Conventional charging loads exhibit a plateau shape in the afternoon when vehicles are centralized at workplaces and charging capacity is limited. They exhibit sharp peaks in the evening when vehicles are distributed at residences and charging capacity is nearly ubiquitous.
- The timing of conventional charging coincides with peak conventional loads and thus is more likely to require power generation capacity expansion. In contrast, online charging is much less synchronized and is less likely to require as much of an increase.
- The sharp peaks that characterize online transportation electrification require substantial operating reserves for reliable power grid operation. These incur additional operating costs relative to a conventional charging scenario.

VII. Future Work: Intelligent Transportation Energy Systems

A consistent theme in this book chapter has been the potential role of an intelligent transportation-energy system, as first mentioned in [12]. The physical coupling of the transportation and power systems brings about the coupled operations management decision shown in Table I. The first step to designing such an ITES begins with a deep understanding of the nature of the coupling in the form of a rigorous quantitative model such as the one presented in this work. This model must then be simulated to demonstrate these couplings. Test cases play an important role in that regard as they offer insight and intuition into fundamental dynamics rather than moving directly to case study results. Ultimately, the control and optimization methods developed within an intelligent transportation-energy system must demonstrate their benefits on arbitrary topologies and not just a specific region.

As this chapter has demonstrated, the potential benefits of an ITES are great. In conventional charging, an ITES can serve to modify vehicle dispatch and route choice and manage queues so as to minimize the waiting time for charging. This leads to direct improvements in the quality of service and expands the use cases for which electric vehicles can be adopted. Charging queue management, coordinated charging and vehicle-2-grid stabilization also serve to reshape the charging load profile for both technical and economic benefits on the power grid. In the case of online electric vehicles, quality of service has been effectively guaranteed. However, an ITES can still modify vehicle dispatch and route choice and also implement coordinated charging and vehicle-2-grid stabilization to smoothen charging loads that will directly follow traffic congestion. In both cases, the implementation of an ITES leads to direct savings in investment and operating costs. Shifting the timing of charging peaks avoids the installation of peak load capacity. Meanwhile flattening the shape of charging loads means that fewer operating reserves will ultimately be required. An intelligent transportation-energy system, therefore, presents a valuable opportunity to improve the techno-economic case for a sustainable and electrified transportation system. And while multi-modal transportation electrification systems present formidable challenges for future work, it is likely that they will ultimately be facilitated by recent advances in connected vehicle technology and multi-agent systems.

APPENDIX

The hybrid dynamic system model presented in Section II is based upon graph theory, petri-nets and axiomatic design for large flexible systems. As the first two of these subjects are from different disciplines, a brief introduction to their fundamental concepts is provided for the potentially uninitiated reader.

A. Graph Theory

Graph theory is a long established field of mathematics with applications in many fields of science and engineering where artifacts are transported between physical locations [42]–[44]. A number of definitions are introduced for later use in the discussion.

Definition 12. Graph [43]: $G = \{B, E\}$ consists of a collection of nodes B and collection of edges E. Each edge $e \in E$ is said to join two nodes, which are called its end points. If e joins $b_1, b_2 \in B$, we write $e = \langle b_1, b_2 \rangle$. Nodes b_1 and b_2 in this case are said to be adjacent. Edge e is said to be incident with nodes b_1 and b_2, respectively.

Definition 13. Bipartite Graph [43]: Graph G is bipartite if $B(G)$ can be partitioned into two disjoint subsets B_1 and B_2 such that each edge $e \in E(G)$ has one end point in B_1 and the other in B_2: $E(G) \subseteq \{e = \langle b_1, b_2 \rangle | b_1 \in B_1, \text{ and } b_2 \in B_2\}$.

Definition 14. Directed Graph (digraph) [43]: D, consists of a collection nodes B, and a collection of arcs E, for which we write $D = (B, E)$. Each arc $e = \langle b_1, b_2 \rangle$, is said to join node $b_1 \in B$ to another (not necessarily distinct) node b_2. Vertex b_1 is called the tail of e, whereas b_2 is its head.

Definition 15. Incidence In Matrix [43]: M^+ of size $\sigma(B) \times \sigma(E)$ is given by:

$$M^+(i,j) = \begin{cases} 1 & \text{if } b_y \text{ is the tail of arc } e_j \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

where the operator $\sigma()$ gives the size of a set.

Definition 16. Incidence Out Matrix [43]: M^- of size $\sigma(B) \times \sigma(E)$ is given by:

$$M^-(i,j) = \begin{cases} 1 & \text{if } b_y \text{ is the head of arc } e_j \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

Definition 17. Incidence matrix [43]: M of size $\sigma(B) \times \sigma(E)$ is given by:

$$M = M^+ - M^- \tag{15}$$

Definition 18. Adjacency matrix [43]: A, is binary and of size $\sigma(B) \times \sigma(B)$ and its elements are given by:

$$A(y_1, y_2) = \begin{cases} 1 & \text{if } \langle b_{y_1}, b_{y_2} \rangle \text{ exists} \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

B. Petri-Nets

Petri-nets offer a long established method for modeling and simulating the discrete-event dynamics of a system. Their usage is described by the following definitions.

Definition 19. Marked Petri Net (Graph) [45]: A bipartite directed graph represented as a 5-tuple $\mathcal{N} = (B, \mathcal{E}, A, W, Q_B)$ where:

- B is a finite set of places of size $\sigma(B)$.
- $\mathcal{E}$ is a finite set of (instantaneous) transitions/events of size $\sigma(\mathcal{E})$.
- $M \subseteq (B \times \mathcal{E}) \cup (\mathcal{E} \times B)$ is a set of arcs of size $\sigma(M)$ from places to transitions and from transitions to places in the graph.
- $W : A \to \{0, 1\}$ is the weighting function on arcs.
- Q_B is a marking (or discrete state) vector of size $\sigma(B) \times 1 \in \mathbb{N}^{\sigma(B)}$.

As with graphs, three incidence matrices are defined for petri-nets.

Definition 20. Petri-Net Incidence In Matrix [45]: $M_{\mathcal{N}}^{+}$ of size $\sigma(B) \times \sigma(\mathcal{E})$ is given by:

$$M_{\mathcal{N}}^{+}(i,j) = \begin{cases} 1 & \text{if } b_y \text{ is the tail of event } \epsilon_j \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

Definition 21. Petri-Net Incidence Out Matrix [45]: $M_{\mathcal{N}}^{-}$ of size $\sigma(B) \times \sigma(\mathcal{E})$ is given by:

$$M_{\mathcal{N}}^{-}(i,j) = \begin{cases} 1 & \text{if } b_y \text{ is the head of event } \epsilon_j \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

Definition 22. Petri Net Incidence matrix [45]: $M_{\mathcal{N}}$ of size $\sigma(B) \times \sigma(\mathcal{E})$ is given by:

$$M_{\mathcal{N}} = M_{\mathcal{N}}^{+} - M_{\mathcal{N}}^{-} \tag{19}$$

Definition 23. Petri Net (Discrete-Event) Dynamics [45]: Given a binary firing vector U_{Dk} of size $\sigma(\mathcal{E}) \times 1$ and a petri-net incidence matrix $M_{\mathcal{N}}$ of size $\sigma(B) \times \sigma(\mathcal{E})$, the evolution of the marking vector Q_B is given by the state transition function $\Phi(Q_B, U_{Dk})$:

$$Q_B[k+1] = \Phi(Q_B, U_{Dk}) = Q_B[k] + M_{\mathcal{N}} U_k \tag{20}$$

While marked petri-nets are sufficient for discrete-event dynamics, they do assume events of infinitesimal duration. In the case of transportation systems, it is necessary to associate a duration to each of these events which may be either deterministic [46] or stochastic [88]. The former is defined as follows:

Definition 24. Timed Petri Net (Graph) [46]: A 6-tuple $\mathcal{N}_T = (B, \mathcal{E}, A, W, Q, D)$ where $(B, \mathcal{E}, A, W, Q)$ is a marked petri net where Q is marking vector of size $[\sigma(B)+\sigma(\mathcal{E})] \times 1 \in \mathbb{N}^{[\sigma(B)+\sigma(\mathcal{E})]}$ that includes marking of events $Q_{\mathcal{E}}$ in addition to the marking of places Q_B. $Q = [Q_B; Q_{\mathcal{E}}]$. D is a duration vector of size $\sigma(\mathcal{E}) \times 1$ representing the finite duration required to fire the event.

The following petri-net dynamics are used in the context of this work.

Definition 25. Timed Petri Net (Discrete-Event) Dynamics: The evolution of the marking vector $Q = [Q_B; Q_{\mathcal{E}}]$ is given by the state transition function $Q[k+1] = \Phi_T\left(Q[k], U_k^{+}, U_k^{-}\right)$.

$$Q_B[k+1] = Q_B[k] + M_{\mathcal{N}}^{+} U_k^{+} - M_{\mathcal{N}}^{-} U_k^{-} \tag{21}$$
$$Q_{\mathcal{E}}[k+1] = Q_{\mathcal{E}}[k] - U_k^{+} + U_k^{-} \tag{22}$$

where U_k^{-} is the k^{th} input firing vector and U_k^{+} is k^{th} output firing vector.

The input firing vector U_{Dk}^{-} is taken as exogenous while the output firing vector U_{Dk}^{+} is calculated from the event durations D by means of a scheduled event list.

The state transition function in Definition 25 has a minor modification from the one commonly used elsewhere in the petri-net literature [46]. Normally, tokens remain in place until the event duration has passed. Here, the tokens are taken from the place marking vector and appear instead in the transition marking vector. They reappear in the marking vector after the event duration has passed. This modification is made so that the petri-net dynamics more closely represent the physical reality as described in Section II. The rules of timed petri-net operation, including when transitions are enabled, remain otherwise the same.

Definition 26. Scheduled Event List [45]: A tuple $\mathcal{S} = (u_{vk}, t_k)$ consisting of all elements u_{vk} in firing vectors U_k and their associated times t_k. For every element, $u_{vk}^{-} \in U_k^{-}$, there exists another element $u_{vk}^{+} \in U_k^{+}$ which occurs at $t = t_k + d_v$.

The output firing vectors U_{Dk}^{+} are then calculated from their elements for all the unique times $t = t_k + d_v$.

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